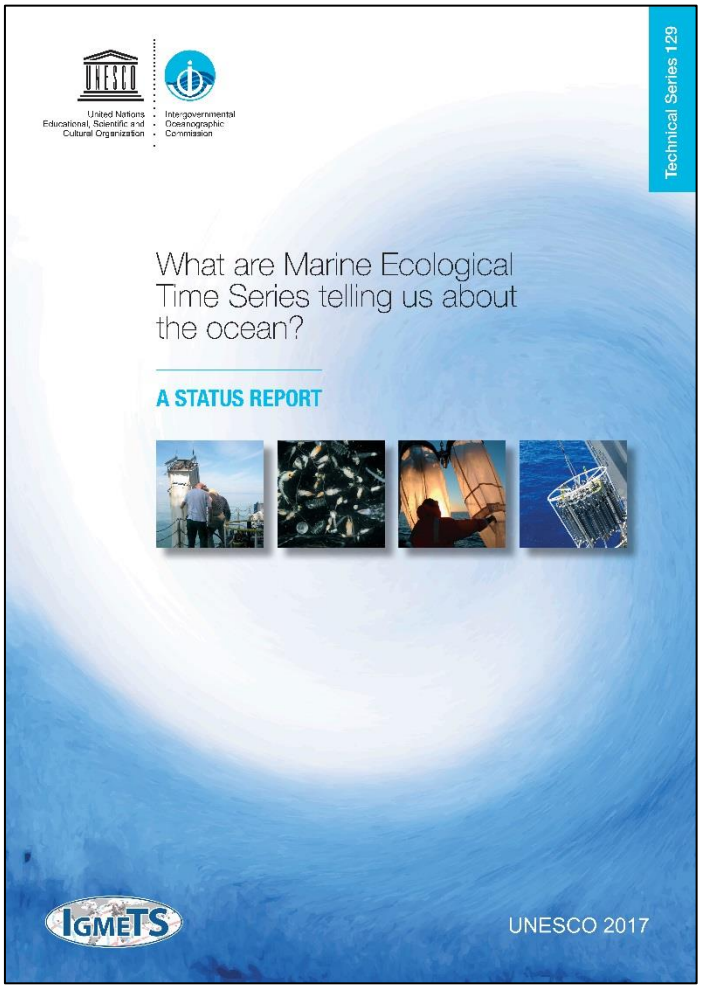
What are Marine Ecological Time Series telling us about the ocean? A status report

[Individual Chapter (PDF) download]

The full report (all chapters and Annex) is available online at:

http://igmets.net/report



This page intentionally left blank

to preserve pagination in double-sided (booklet) printing

10 Global Overview

Laura Lorenzoni, Todd D. O'Brien, Kirsten Isensee, Heather Benway, Frank E. Muller-Karger, Peter A. Thompson, Michael Lomas, and Luis Valdés

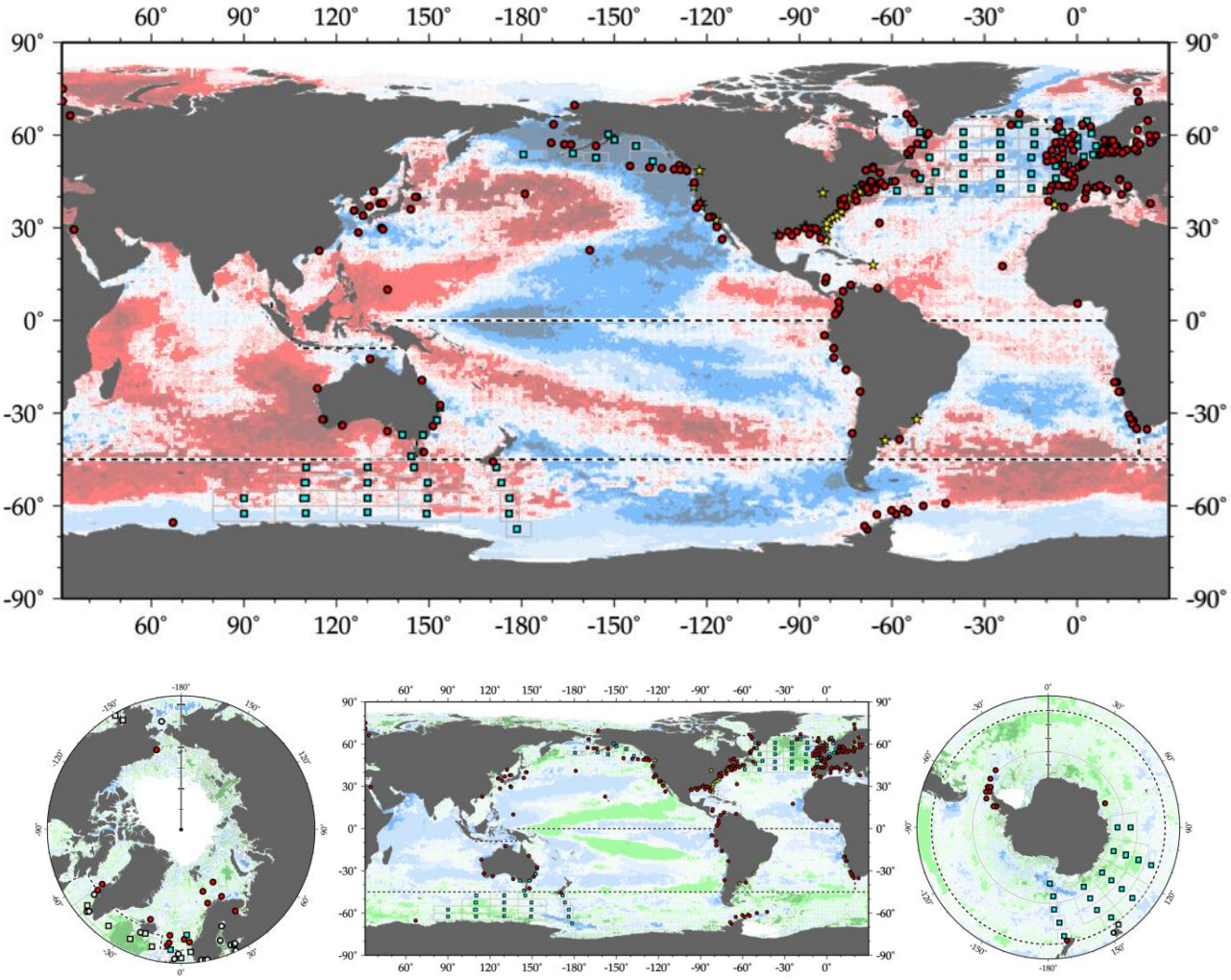


Figure 10.1. Maps of IGMETS-participating time series on a background of 10-year (2003–2012) sea surface temperature trends (top panel, see also Figure 10.4a) or on a background of 10-year sea surface chlorophyll trends (bottom panel, see also Figure 10.4b). These maps show 344 time series (coloured symbols of any type), of which 71 were from Continuous Plankton Recorder subareas (blue boxes) and 46 were from estuarine areas (yellow stars). Dashed lines indicate boundaries between IGMETS regions. Additional information on the sites in this study is presented in the Annex.

Participating time-series investigators

Eric Abadie, Jose L. Acuna, M. Teresa Alvarez-Ossorio, Anetta Ameryk, Jeff Anning, Elvire Antajan, Georgia Asimakopoulou, Yrene Astor, Angus Atkinson, Patricia Ayon, Alexey Babkov, Hermann Bange, Ana Barbosa, Nick Bates, Uli Bathmann, Sonia Batten, Beatrice Bec, Radhouan Ben-Hamadou, Claudia Benitez-Nelson, Carla F. Berghoff, Robert Bidigare, Antonio Bode, Maarten Boersma, Angel Borja, Alexander Brearley, Eileen Bresnan, Cecilie Broms, Juan Bueno, Mario O. Carignan, Craig Carlson, David Caron, Jacob Carstensen, Gerardo Casas, Benoit Casault, Claudia Castellani, Fabienne Cazassus, Georgina Cepeda, Paulo Cesar Abreu, Jacky Chauvin, Sanae Chiba, Luis Chicharo, Epaminondas Christou, Matthew J. Church, Andrew Clarke, James E. Cloern, Rudi Cloete, Nathalie Cochennec-Laureau, Andrew Cogswell, Amandine Collignon, Yves Collos, Frank Coman, Maria Constanza Hozbor, Kathryn Cook, Dolores Cortes, Joana Cruz, Daniel Cucchi Colleoni, Kim Currie, Padmini Dalpadado, Claire Davies, Alejandro de la Sota, Alessandra de Olazabal, Laure Devine, Emmanuel Devred, Iole Di Capua, Rita Domingues, Anne Doner, John E. Dore, Antonina dos Santos, Hugh Ducklow, Janet Duffy-Anderson, Joerg Dutz, Martin Edwards, Lisa Eisner, Joao Pedro Encarnacao, Ruth Eriksen, Ruben Escribano, Luisa Espinosa, Tone Falkenhaug, Ana Faria, Ed Farley, Maria Luz Fernandez de Puelles, Susana Ferreira, Bjorn Fiedler, Jennifer L. Fisher, James Fishwick, Serena Fonda-Umani, Almudena Fontan, Janja France, Javier Franco, Jed Fuhrman, Mitsuo Fukuchi, Eilif Gaard, Moira Galbraith, Peter Galbraith, Helena Galvao, Pep Gasol, Amatzia Genin, Astthor Gislason, Anne Goffart, Renata Goncalves, Rafael Gonzalez-Quiros, Gabriel Gorsky, Annika Grage, Hafsteinn Gudfinnsson, Kristinn Gudmundsson, Valeria Guinder, Troy Gunderson, David Hanisko, Jon Hare, Roger Harris, Erica Head, Jean-Henri Hecq, Simeon Hill, Richard Horaeb, Graham Hosie, Jenny Huggett, Keith Hunter, Anda Ikauniece, Arantza Iriarte, Masao Ishii, Solva Jacobsen, Marie Johansen, Catherine Johnson, Jacqueline Johnson, Young-Shil Kang, David M. Karl, So Kawaguchi, Kevin Kennington, Diane Kim, Georgs Kornilovs, Arne Kortzinger, Alexandra Kraberg, Anja Kreiner, Nada Krstulovic, Takahashi Kunio, Inna Kutcheva, Michael Landry, Bertha E. Lavaniegos, Aitor Laza-Martinez, Jesus Ledesma Rivera, Alain Lefebvre, Sirpa Lehtinen, Maiju Lehtiniemi, Ezequiel Leonarduzzi, Ricardo M. Letelier, William Li, Priscilla Licandro, Michael Lomas, Christophe Loots, Angel Lopez-Urrutia, Laura Lorenzoni, Roger Lukas, Vivian Lutz, Dave Mackas, Jorge Marcovecchio, Francesca Margiotta, Piotr Margonski, Roberta Marinelli, Jennifer Martin, Douglas Martinson, Daria Martynova, Daniele Maurer, Maria Grazia Mazzocchi, Sam McClatchie, Felicity McEnnulty, Webjorn Melle, Jesus M. Mercado, Michael Meredith, Claire Meteigner, Ana Miranda, Graciela N. Molinari, Nora Montoya, Pedro Morais, Cheryl A. Morgan, Patricija Mozetic, Teja Muha, Frank Muller-Karger, Jeffrey Napp, Florence Nedelec, Ruben Negri, Vanessa Neves, Todd D. O'Brien, Clarisse Odebrecht, Mark Ohman, Lena Omli, Emma Orive, Luciano Padovani, Hans Paerl, Marcelo Pajaro, Evgeny Pakhomov, Kevin Pauley, S.A. Pedersen, Ben Peierls, Pierre Pepin, Myriam Perriere Rumebe, Ian Perry, Tim Perry, William T. Peterson, Roger Pettipas, David Pilo, Sophie Pitois, Al Pleudemann, Stephane Plourde, Arno Pollumae, Dwayne Porter, Lutz Postel, Nicole Poulton, Igor Primakov, Regina Prygunkova, A. Miguel P. Santos, Andy Rees, Michael Reetz, Beatriz Reguera, Malcolm Reid, Christian Reiss, Jasmin Renz, Mickael Retho, Marta Revilla, Maurizio Ribera, Anthony Richardson, Malcolm Robb, Marie Robert, Don Robertson, Karen Robinson, M. Carmen Rodriguez, Andrew Ross, Gunta Rubene, M. Guillermina Ruiz, Tatiana Rynearson, Sei-ichi Saitoh, Rafael Salas, Danijela Santic, Diana Sarno, Michael Scarratt, Renate Scharek, Oscar Schofield, Mary Scranton, Valeria Segura, Sergio Seoane, Stefanija Sestanovic, Yonathan Shaked, Volker Siegel, Mike Sieracki, Joe Silke, Ricardo I. Silva, Ioanna Siokou-Frangou, Milijan Sisko, Anita Slotwinkski, Tim Smyth, Mladen Solic, Dominique Soudant, Carla Spetter, Jeff Spry, Michel Starr, Debbie Steinberg, Deborah Steinberg, Lars Stemmann, Rowena Stern, Solvita Strake, Patrik Stromberg, Glen Tarran, Gordon Taylor, Maria Alexandra Teodosio, Peter Thompson, Robert Thunell, Valentina Tirelli, Others to be added soon, Mark Tonks, Sakhile Tsotsobe, Ibon Uriarte, Julian Uribe-Palomino, Nikolay Usov, Luis Valdés, Victoriano Valencia, Marta M. Varela, Hugh Venables, Marina Vera Diaz, Hans Verheye, Olja Vidjak, Fernando Villate, Maria Delia Viñas, Norbert Wasmund, Robert Weller, George Wiafe, Claire Widdicombe, Karen H. Wiltshire, Malcolm Woodward, Lidia Yebra, Kedong Yin, Cordula Zenk, Soultana Zervoudaki, and Adriana Zingone

This chapter should be cited as: Lorenzoni, L., O'Brien, T. D., Isensee, K., Benway, H., Muller-Karger, F. E., Thompson, P. A., Lomas, M., *et al.* 2017. Global Overview. I*n* What are Marine Ecological Time Series telling us about the ocean? A status report, pp. 171–190. Ed. by T. D. O'Brien, L. Lorenzoni, K. Isensee, and L. Valdés. IOC-UNESCO, IOC Technical Series, No. 129. 297 pp.

10.1 Introduction

The ocean's biological, physical, and chemical characteristics vary across a range of temporal and spatial scales in response to different driving forces. These include short-term and seasonal localized phenomena, such as coastal upwelling and river discharge, as well as meso- and large-scale features like eddies, ocean currents, and the global thermohaline circulation – the conveyor belt (Figure 10.2). The ocean also responds to large-scale climate cycles (e.g. Pacific Decadal Oscillation, El Niño–Southern Oscillation, North Atlantic Oscillation). Changes induced by humans add yet another layer of complexity. Monitoring changes in global marine biological and biogeochemical variables and exploring their relationships with natural variability and anthropogenic forcing is fundamental to improving our capacity to predict how the ocean may respond to future changes as well as associated impacts on marine ecosystem services (Worm *et al*., 2006; Hoegh-Guldberg and Bruno, 2010; Overland *et al*., 2010; Doney *et al*., 2014).

Global ocean phytoplankton biomass and sea surface temperature (SST) have been investigated with a variety of techniques, including satellites and *in situ* sampling. These two variables have significant effects on ecosystem structure and functioning and have been observed to change in response to varying ocean conditions (IPCC, 2013). Several authors have suggested that global phytoplankton biomass has declined over the past several decades in nearly all ocean regions due to increasing SST and stratification (Behrenfeld *et al*., 2006; Henson *et al*., 2010; Vantrepotte and Mélin, 2009, 2011; Beaulieu *et al*., 2013; IPCC, 2013; Siegel *et al*., 2013), while others point to an increase in the North Atlantic where long time series exist (McQuatters-Gollop *et al*., 2011). The relationship among SST, chlorophyll and stratification, however, is not simple; therefore, it is difficult to correlate changes in one with changes in the other on a global scale (Dave and Lozier, 2013; Behrenfeld *et al*., 2015).

Maps of trends help identify regions that experience significant changes over different time-scales and can also provide information on rates of change. Maps of multiple variables help elucidate possible causes for the alterations. Changes are constantly occurring on a global scale; some are related to anthropogenic forcing, and some variables will show changes faster than others, resulting in a widespread debate on the length of time required to observe trends related to climate signals (Henson *et al*., 2010, 2016; Henson, 2014).

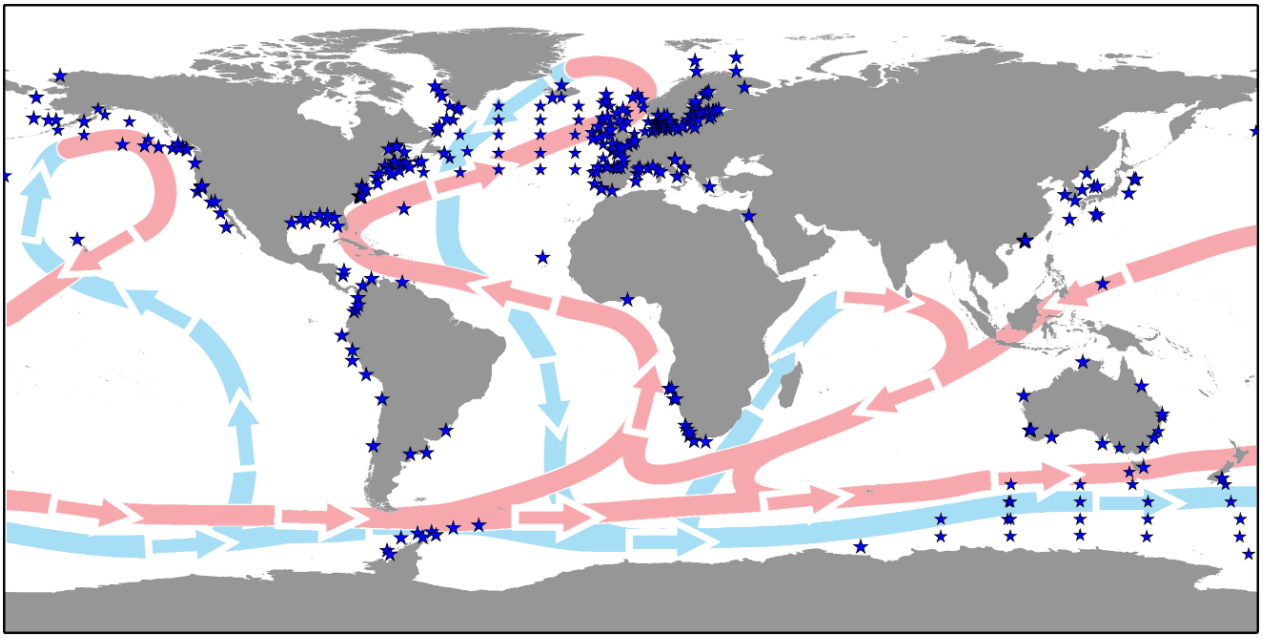


Figure 10.2. Map showing stylized, major global currents that interconnect the world oceans, also known as "the conveyor belt". Blue arrows indicate generally cooler water currents and red arrows indicate generally warmer currents. The dark blue stars indicate the locations of the 344 time series that participated in this study. Additional information on these time series is presented in the Annex.

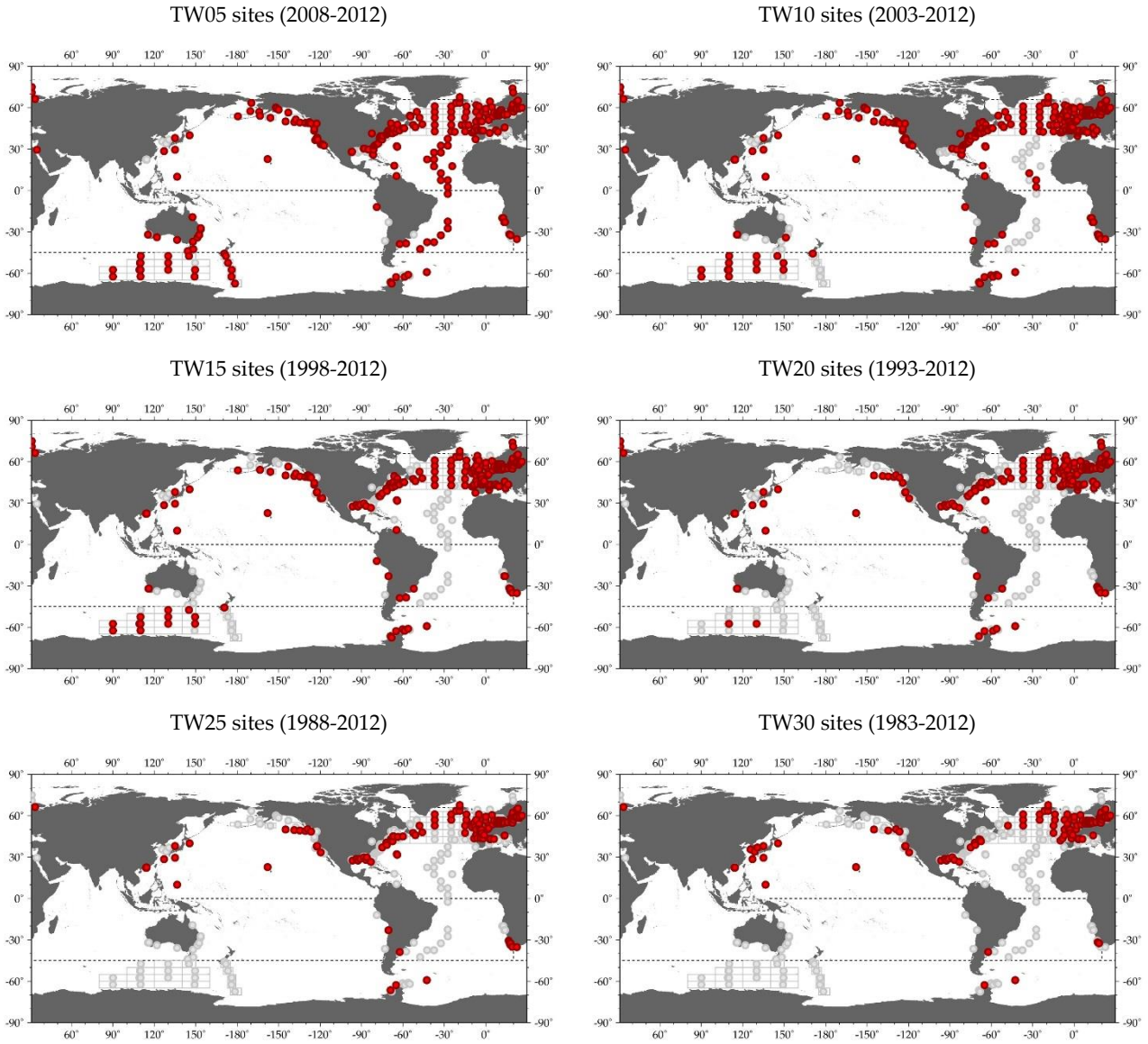


Figure 10.3. Panel of maps showing locations of IGMETS-participating time series based on time-window qualification. Red symbols indicate time-series sites with at least one biological or biogeochemical variable (i.e. excluding temperature- and salinity-only time series) that qualified for that time-window (e.g. TW05, TW20). Light gray symbols indicate sites that did not have enough data from the given time-window to be included in that analysis.

Globally, there are at least 344 ship-based biogeochemical time series that span different lengths and windows of time (Figure 10.1). These time series represent one of the most valuable tools scientists have to characterize and quantify ocean carbon fluxes, biogeochemical processes, and their links to changing climate (Karl, 2010; Chavez *et al*., 2011; Church *et al*., 2013). Coupling these *in situ* biogeochemical measurements and plankton data with satellite observations improves the understanding of changes in the biological, physical, and biogeochemical properties of the global oceans. Satellite data provide an additional layer of information about changing ocean conditions and ecosystems and can help scale-up the relatively sparse shipboard datasets to achieve a broader regional and/or global perspective.

In this chapter, we aim to examine changes in the global oceans, explore possible connections between ocean basins, and identify areas that show significant changes over temporal periods of 10, 15, 20, and 30 years ("time-windows"; the IGMETS "time-windows" analysis is described in Chapter 2). A shorter 5-year time-window analysis is also available to observe short-term fluctua-

tions, though these may not be statistically significant for climate change-related trends. Thirty years of observations provide information on the overall direction of change (if any) of the different ocean variables and present a good basis to start distinguishing between natural variability and long-term, human-induced trends (Henson *et al*., 2010; Henson, 2014). In terms of available biogeochemical and plankton time series, there are tenfold more 5-year time series than 30-year time series. However, going back in time (20 years), most of the time-series sites are located in the North Atlantic (Figure 10.3).

Short time-windows, such as five years, provide information on the speed of some of the changes that are being observed in the ocean and offer insight on short-term fluctuations. The magnitude of natural variability in many biogeochemical variables can mask anthropogenic trends, as is shown in the regional chapters. The ecological and economic consequences of such changes are important, particularly with regard to marine ecosystem goods and services. Analyzing changes in specific time-windows facilitates comparison of trends in different areas and detection of decadal and multidecadal climatic drivers. Clearly, the start and end dates chosen for trend analyses may influence the assessment of the rates of change (IPCC, 2013; Karl *et al*., 2015).

It is not possible yet to fully quantify how much of the ocean's variability is due to anthropogenic drivers; hence, the importance of sustained ocean time-series observations. Only a fraction of the biogeochemical time series around the world reaches or exceeds observations of more than two decades (Figure 10.3). Indeed, many ship-based biogeochemical time-series measurements (e.g. ocean CO_2 system parameters, nutrient concentrations), particularly in the southern hemisphere, were initiated only in the past decade. These various time series provide a "baseline" against which to detect areas that have undergone rapid change.

10.2 General patterns of temperature and phytoplankton biomass

Significant trends in SST were visible at the global scale (over 79% of the ocean) during the past three decades (Figure 10.4a; Table 10.1). In the 30-year time-window (1983–2012), 79.9% (69.8% at $p < 0.05$) of the world's oceans increased in temperature, while 20.1% (13.2% at $p < 0.05$) registered a decrease (Table 10.1). The most significant warming was observed in the Atlantic and Indian oceans (Figure 10.4a; see also the respective regional chapters). Comparing the changes, the positive trend was +0.1 to +0.5°C decade^{-1}. Areas that cooled down had rates of less than –0.1°C decade^{-1}. These observations generally agree with published results that highlight increases in ocean temperatures of ca. 0.1°C decade^{-1} (IPCC, 2013; Karl *et al*., 2015). Non-significant changes were visible only in the western and tropical Pacific Ocean, a portion of the South Atlantic, and in small areas of the Arctic and Antarctic oceans. The warming trend is also visible over a large portion of the global ocean during the past 10–15 years (49.3% in the past 10 years, with 26.3% at $p < 0.05$; 69.3% over the past 15 years, with 44.8% at $p < 0.05$; Figure 10.4a; Table 10.1).

Satellite data coverage of the Arctic region is poor. Changes in SST show that this area is subject to strong interannual and spatial variability linked to changes in albedo (sea ice cover, soot on snow), atmospheric cloud cover, water vapor and black carbon content, and oceanic heat flux (see Serreze and Barry, 2011; and references therein). Compared to the Antarctic (with the exception of the Western Antarctic Peninsula; Meredith and King, 2005; Steig *et al*., 2009), warming over the Arctic during 1983–2012 has been pronounced (85.3%, with 79.2% at $p < 0.05$). While the Arctic Ocean showed a slowdown in its warming during 2003–2012, positive SST trends have prevailed.

In the Southern Ocean, 55.9% (with 44% at $p < 0.05$) of the region cooled during 1983–2012 (Figures 10.4a and 10.5). Areas of cooling are close to the Antarctic coastline, while the warming is observed farther north. One exception is the area adjacent to the Western Antarctic Peninsula; this warming arises largely from increased air temperatures recorded in the region and reduced sea ice cover (Meredith and King, 2005; Steig *et al*., 2009; Ducklow *et al*., 2013). Variations in the Antarctic SST are associated with changes in the polarity of the Southern Oscillation (SO) and the Southern Annular Mode (SAM), as well as the Antarctic Oscillation Index (AAO) (Yu *et al*., 2012). Some of the colder SSTs observed could be attributed to lower air temperatures reported for a large portion of the Antarctic Peninsula (Kwok and Comiso, 2002; Marshall *et al*., 2014). The driver of these negative SST trends is still being debated (Randel and Wu, 1999; Thompson and Solomon, 2002). Over the 15-year time-window, significant warming was observed in most of the measurable surface of the

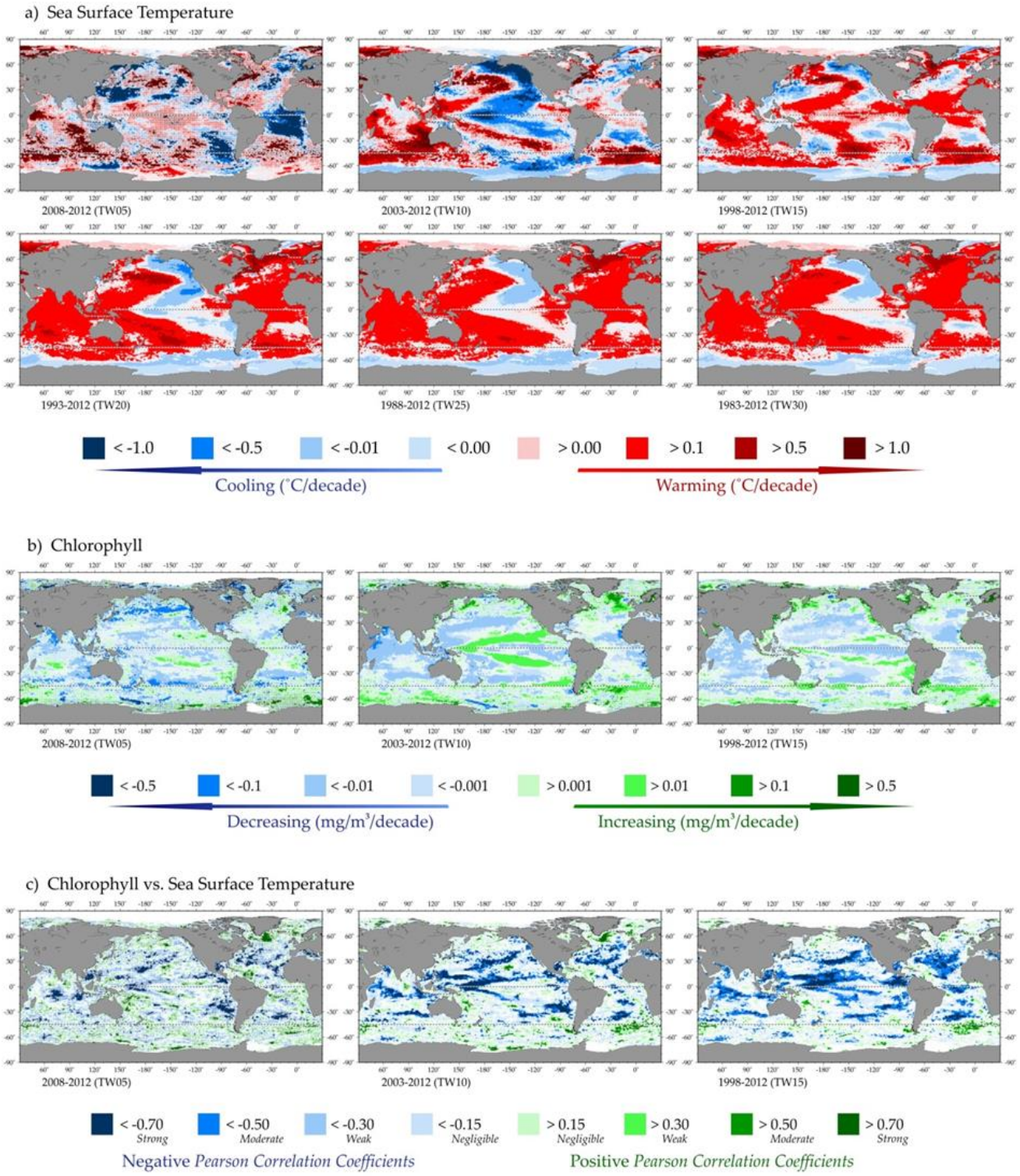


Figure 10.4. Annual trends in global sea surface temperature (SST) (a) and sea surface chlorophyll (CHL) (b) and correlations between chlorophyll and sea surface temperature for each of the standard IGMETS time-windows (c). See "Methods" chapter for a complete description and methodology used.

Southern Ocean (57.5%, of which 40.0% was significant at $p < 0.05$; Table 6.1; Figure 6.2). This pattern reversed over the past 10 years, where ca. 54% of the Southern Ocean exhibited cooling (Table 6.1; Figure 6.2). The Western Antarctic Peninsula was still the exception, where sustained warming was observed in both time-windows (Meredith and King, 2005; Ducklow *et al*., 2013; see Chapter 6). The cooling in the past decade has been, in part, attributed to the ozone hole (Marshall *et al*., 2014).

In the Atlantic Ocean, the subtropical South Atlantic cooling observed over the 30-year time-period is possibly linked to variations in the subtropical anticyclone that arises from decadal-scale, wind-driven ocean temperature fluctuations that occur in a north–south dipole structure (Venegas *et al*., 1997). It could also be a manifestation of an ENSO teleconnection (Nobre and Shukla, 1996; Enfield and Mestas-Nuñez, 2000; Deser *et al*., 2010). The warming of the entire North Atlantic region (99.1%, with 97.3% at $p < 0.05$) over the past three decades has been attributed to both natural and anthropogenic forcings (Knudsen *et al*., 2011; Hoegh-Guldberg *et al*., 2014). Over shorter time-scales, the warming and cooling across the Atlantic were more heterogeneous; during 2003–2012, 50.3% of the Atlantic – the southern north and south parts – warmed, while 49.7% – the northern North and South Atlantic – cooled. In the North Atlantic, air temperatures are largely driven by the NAO, with colder conditions over the Mediterranean and subpolar regions and warmer mid-latitudes (Europe, the north-eastern United States, and parts of Scandinavia) during positive NAO phases (Visbeck *et al*., 2001; Deser *et al*., 2010; Hurrell and Deser, 2010). For this phase, SST reflects a "tripole pattern" with a cold anomaly in the subpolar region, a warm anomaly in the mid-latitudes, and a cold subtropical anomaly between 0 and 30°N (Visbeck *et al*., 2001). The mixed warm/cold trends observed in the North Atlantic over the past decade could be reflecting fluctuations of NAO phases (e.g. strong negative phases in 2009 and 2010, positive in 2012), and possible SST feedback (Hurrell and Deser, 2010; Figure 10.4). The colder SST could also be the result of changes in the Atlantic meridional overturning circulation (AMOC), as suggested by Rahmstorf *et al*. (2015).

Cooling observed in the western and tropical Pacific Ocean over the past 30 years is likely related to interannual–multidecadal oscillations like the El Niño Southern Oscillation (ENSO), the Interdecadal Pacific Oscillation (IPO), and the Pacific Decadal Oscillation (PDO) (Chavez *et al*., 2003, 2011). Pacific SST is strongly correlated with these climate indices (Enfield *et al*., 2001; Alexander *et al*., 2002). The warming and cooling of the Pacific under the changing regimes is not uniform; the central North and South Pacific are out of phase with the eastern Pacific. Chavez *et al*. (2003) identified one "warm" period (from about 1975 to the late 1990s) and two cooler periods (from the early 1950s to about 1975 and from the late 1990s to around 2012). In the 15-year time-window, a particular pattern emerged in the Pacific Ocean with warming across the equatorial Pacific. In 1998–2012, 65.2% of the Pacific warmed (37% at $p < 0.05$), and these areas were located mostly near the equator and in the central North and South Pacific; 34.8% cooled (17.0% at $p < 0.05$; see Figure 7.2). That pattern can be tied to ENSO (Deser *et al*., 2010). However, when analyzing the 10-year time-window, the Pacific exhibited a general cooling over 59% of its area (40% at $p < 0.05$). This is largely linked to La Niña-like conditions (Kosaka and Xie, 2013) and a change in phase of IPO from positive to negative around 1998/1999 (Dong and Zhou, 2014).

The Indian Ocean exhibited strong, consistent warming across all time-windows. From 1983 to 2012, 97.8% of the Indian Ocean warmed (91.9% at $p < 0.05$; Figure 10.4). The warming is associated with a range of climate cycles, including the IPO (Han *et al*., 2014). Over shorter time-scales (10–15 years), while the sustained warming prevailed, the spatial extent decreased (Table 10.1), likely due to variability induced by shorter-term climatic signals (e.g. Indian Ocean Dipole, ENSO).

The chlorophyll (Chl *a*) trends, as derived from satellite data, show that, overall, ca. 60% of the ocean has exhibited decreasing concentrations over the past 15 years (Figures 10.4 and 10.5), which is consistent with previous studies (Polovina *et al*., 2008; Henson *et al*., 2010; Siegel *et al*., 2013; Gregg and Rousseaux, 2014; Signorini *et al*., 2015). In general, changes in chlorophyll are inversely related to SST (Table 10.1; Figure 10.4). The increase in global Chl *a* concentrations observed in the 10-year time-window, relative to the 15-year window, might be attributable to somewhat cooler SSTs. In the Pacific Ocean, in particular, higher Chl *a* concentrations were observed in the subtropics, between roughly 10 and 30°, both north and south of the equator. This region corresponds to areas experiencing cooling and possibly becoming more productive (increased mixed-layer depth), due to La Niña-like conditions (Siegel *et al*., 2013; Signorini *et al*., 2015). The influences of circulation pat

Table 10.1. Relative spatial areas (% of the total region) and rates of change that are showing increasing or decreasing trends in sea surface temperature (SST) for each of the standard IGMETS time-windows. Numbers in brackets indicate the % area with significant ($p < 0.05$) trends. See "Methods" chapter for a complete description and methodology used.

Latitude-adjusted SST data field surface area = 361.9 million km²	**5-year** (2008–2012)	**10-year** (2003–2012)	**15-year** (1998–2012)	**20-year** (1993–2012)	**25-year** (1988–2012)	**30-year** (1983–2012)
Area (%) w/ increasing SST trends ($p < 0.05$)	**52.9%** (*14.8%*)	49.3% (*26.3%*)	**69.3%** (*44.8%*)	**74.1%** (*60.8%*)	**79.4%** (*67.5%*)	**79.9%** (*69.8%*)
Area (%) w/ decreasing SST trends ($p < 0.05$)	47.1% (*16.4%*)	**50.7%** (*29.7%*)	30.7% (*15.0%*)	25.9% (*15.6%*)	20.6% (*13.0%*)	20.1% (*13.2%*)
> 1.0°C decade^{-1} warming ($p < 0.05$)	14.3% (*9.4%*)	4.2% (*4.2%*)	0.6% (*0.6%*)	0.1% (*0.1%*)	0.0% (*0.0%*)	0.0% (*0.0%*)
0.5 to 1.0°C decade^{-1} warming ($p < 0.05$)	14.5% (*3.8%*)	11.3% (*10.6%*)	7.3% (*7.2%*)	6.0% (*6.0%*)	1.9% (*1.9%*)	1.6% (*1.6%*)
0.1 to 0.5°C decade^{-1} warming ($p < 0.05$)	17.4% (*1.3%*)	25.0% (*11.2%*)	46.4% (*35.2%*)	**54.9%** (*51.7%*)	**59.6%** (*58.5%*)	**58.4%** (*58.1%*)
0.0 to 0.1°C decade^{-1} warming ($p < 0.05$)	6.8% (*0.3%*)	8.8% (*0.3%*)	15.1% (*1.8%*)	13.1% (*3.0%*)	17.8% (*7.0%*)	19.9% (*10.1%*)
0.0 to –0.1°C decade^{-1} cooling ($p < 0.05$)	5.3% (*0.1%*)	9.5% (*1.4%*)	12.6% (*2.8%*)	12.5% (*4.1%*)	12.6% (*5.4%*)	14.0% (*7.2%*)
–0.1 to –0.5°C decade^{-1} cooling ($p < 0.05$)	14.9% (*0.9%*)	24.2% (*11.9%*)	16.3% (*10.4%*)	12.3% (*10.4%*)	8.1% (*7.6%*)	6.1% (*5.9%*)
–0.5 to –1.0°C decade^{-1} cooling ($p < 0.05$)	12.2% (*4.1%*)	13.2% (*12.6%*)	1.6% (*1.6%*)	1.1% (*1.1%*)	0.0% (*0.0%*)	0.0 %
> –1.0°C decade^{-1} cooling ($p < 0.05$)	14.6% (*11.2%*)	3.9% (*3.8%*)	0.1% (*0.1%*)	0.0 %	0.0 %	0.0 %

Table 10.2 Relative spatial areas (% of the total region) and rates of change that are showing increasing or decreasing trends in phyto-plankton biomass (CHL) for each of the standard IGMETS time-windows. Numbers in brackets indicate the % area with significant ($p < 0.05$) trends. See "Methods" chapter for a complete description and methodology used.

Latitude-adjusted CHL data field surface area = 361.9 million km²	**5-year** (2008–2012)	**10-year** (2003–2012)	**15-year** (1998–2012)
Area (%) w/ increasing CHL trends ($p < 0.05$)	28.9% (*4.9%*)	40.9% (*16.4%*)	37.8% (*14.6%*)
Area (%) w/ decreasing CHL trends ($p < 0.05$)	**71.1%** (*32.1%*)	**59.1%** (*33.7%*)	**62.2%** (*38.4%*)
> 0.50 mg m^{-3} decade^{-1} increasing ($p < 0.05$)	1.6% (*0.6%*)	0.7% (*0.5%*)	0.9% (*0.8%*)
0.10 to 0.50 mg m^{-3} decade^{-1} increasing ($p < 0.05$)	5.1% (*1.4%*)	4.0% (*2.3%*)	3.7% (*2.8%*)
0.01 to 0.10 mg m^{-3} decade^{-1} increasing ($p < 0.05$)	14.5% (*2.7%*)	22.6% (*11.8%*)	17.2% (*8.9%*)
0.00 to 0.01 mg m^{-3} decade^{-1} increasing ($p < 0.05$)	7.7% (*0.2%*)	13.5% (*1.8%*)	16.0% (*2.1%*)
0.00 to –0.0 mg m^{-3} decade^{-1} decreasing ($p < 0.05$)	9.6% (*0.8%*)	17.3% (*5.2%*)	30.1% (*14.9%*)
–0.01 to –0.10 mg m^{-3} decade^{-1} decreasing ($p < 0.05$)	45.3% (*21.4%*)	37.4% (*25.7%*)	30.8% (*22.8%*)
–0.10 to –0.50 mg m^{-3} decade^{-1} (decreasing) ($p < 0.05$)	12.7% (*7.7%*)	3.9% (*2.4%*)	1.2% (*0.6%*)
> –0.50 mg m^{-3} decade^{-1} (decreasing) ($p < 0.05$)	3.4% (*2.1%*)	0.6% (*0.4%*)	0.1% (*0.1%*)

terns caused by the ENSO are clearly distinguishable. Increases over the 10-year time-window are also observed in the Southern Ocean, in the eastern North Atlantic near the Greenland Sea, and in the Arctic Ocean. Similar changes were also noted by other authors (Henson *et al*., 2010; McQuatters-Gollop *et al*., 2011; Siegel *et al*., 2013). Chl *a* changes around Antarctica may be driven by the Antarctic Oscillation, which affects wind intensity and, in turn, mixed-layer depth (Boyce *et al*., 2010). The Chl *a* increases noted in the North Atlantic and Arctic oceans are likely related to the decrease in ice cover and duration (more open water), which have led to associated increases in primary production in the region (Zhang *et al*., 2010; Arrigo and van Dijken, 2011). In general, for the 10-and 15-year time-windows, positive correlations of SST and Chl *a* were more commonly observed at high latitudes, suggesting drivers other than temperature for the enhanced productivity (Doney, 2006). The only ocean basin that showed a consistent decline in Chl *a* concentrations over time was the Indian Ocean, though some regions, such as the South China Sea and the subtropical front, showed no trend.

It is important to stress that the aforementioned trends derived from satellite observations are only for a portion of the surface ocean. Satellite-derived SST and Chl *a* are limited to the first optical depth, which can vary from a few to several tens of metres, depending on the optical properties of the water (Morel *et al*., 2007). It is also important to bear in mind that changes observed in Chl *a* can be associated with physiological changes and changes in phytoplankton biomass or biased by high concentrations of coloured dissolved organic matter (CDOM) (Siegel *et al*., 2005; Behrenfeld *et al*., 2015).

10.3 Trends from *in situ* time series

Only a few *in situ* time series have sufficient data to show reliable trends in biogeochemical variables over the past 30 years. Indeed, the North Atlantic, Baltic Sea, and Mediterranean Sea are some of the only locations where such time-series information exists, which enable us to track how the biology and biogeochemistry may have been changing over the past 30 years. Continuous satellite chlorophyll concentration data are only available since the late 1990s.

Over time-scales of less than a decade, it is difficult to distinguish between natural and anthropogenic forcing

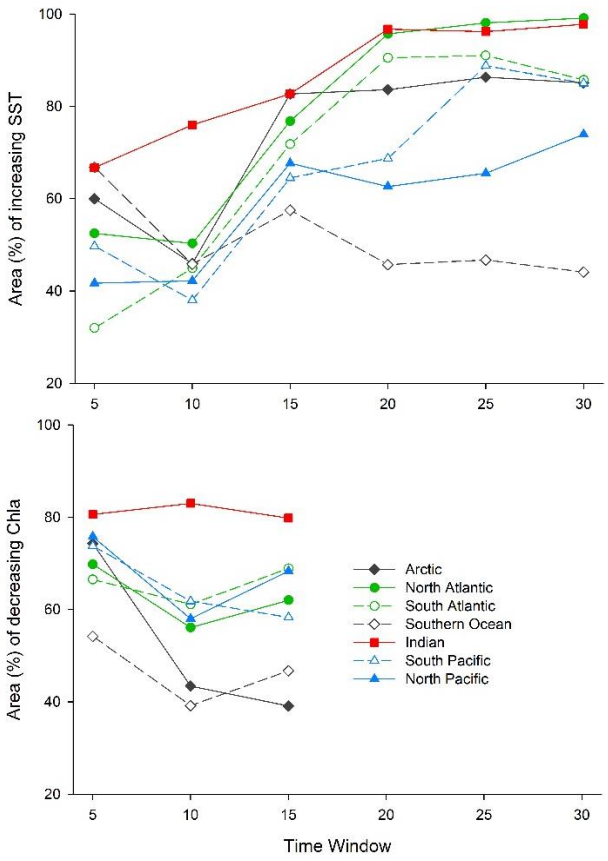


Figure 10.5. Percent spatial area of increasing sea surface temperature (SST; top) and decreasing chlorophyll *a* (Chl *a*; bottom) measurements per ocean over different time-windows, as derived by satellite measurements.

(Overland *et al*., 2006; Karl, 2010; Henson, 2014). Statistical significance of results can also be questionable. For this reason, this chapter's analysis of satellite data was done for time-windows of 10 or more years. However, for *in situ* time series, even short time-scale data provide valuable information. Most of the time series collecting measurements today span ≤ 10 years. Thus, we will provide a short summary of biogeochemical trends from *in situ* time series, especially focusing over the past fifteen, ten, and five years, but, where possible, including those few that have measurements with longer time-spans.

Over the 30-, 15-, 10-, and 5-year periods, most of the *in situ* time-series data report an increase in Chl *a* concentrations throughout the world's oceans, contrasting with some of the satellite data (Table 10.2; Figure 10.9). It is particularly interesting to note that the majority of the time series are located in coastal areas, where local drivers affect primary production and chlorophyll concentrations. Indeed, the *in situ* time series and satellite Chl *a* trends highlight the differences between coastal and

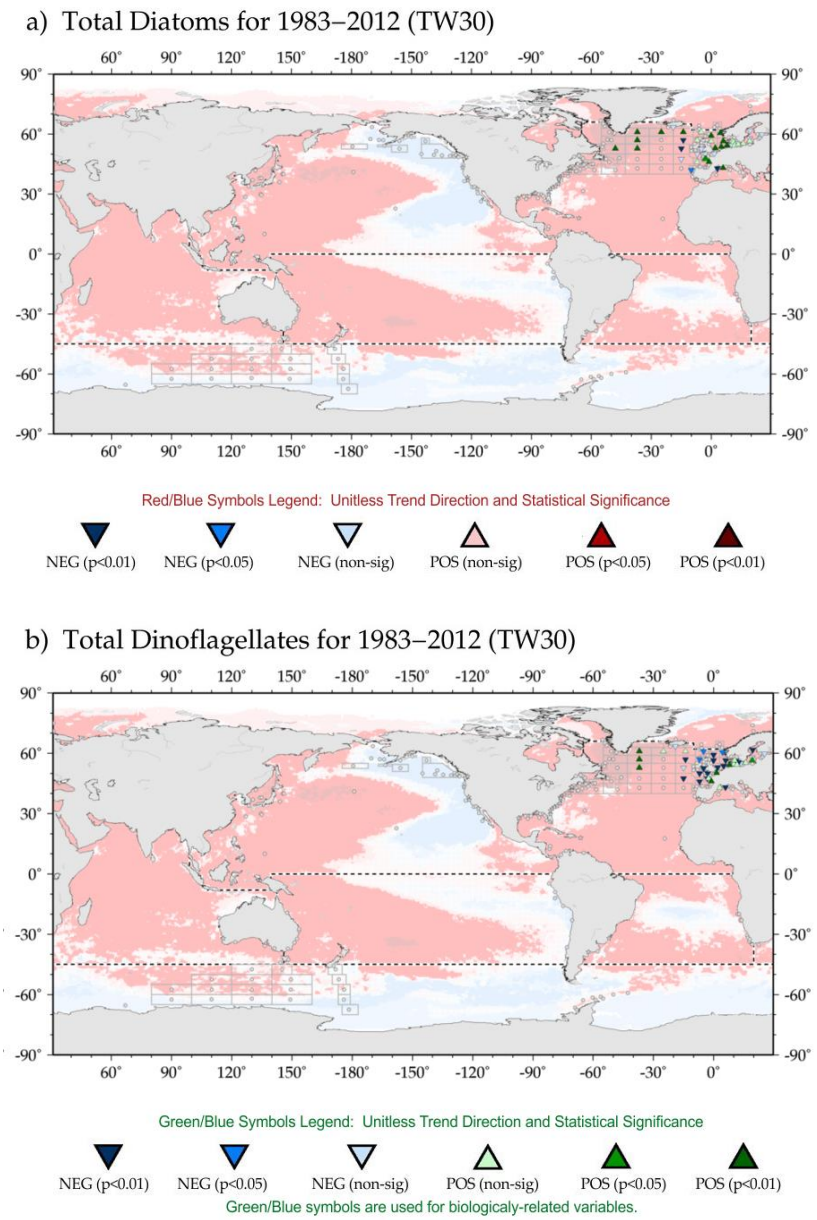


Figure 10.6. Global 30-year trends (1983–2012; TW30) of diatom (a) and dinoflagellate (b) concentrations; background colours indicate rates of change in gridded SST obtained from Reynolds OIv2SST.

open-ocean ecosystems. Special caution must be used when averaging oceanic regions (Yuras *et al*., 2005), and the inclusion of continental margins in primary production or carbon-flux estimates for the world's oceans has to be considered (Laws *et al*., 2000; Müller-Karger *et al*., 2005).

While it is generally accepted that phytoplankton become less abundant with rising ocean temperatures due to increased stratification and less nutrient availability (Richardson and Schoeman, 2004; Gruber, 2011), it has been suggested that global warming can also boost phytoplankton abundance and that phytoplankton physiology responds favorably to such changes (Richardson and Schoeman, 2004; Kempt and Villareal, 2013; Behrenfeld *et al*., 2015). A shift towards more upwelling-favorable winds and subsequently enhanced coastal upwelling in response to greenhouse warming can lead to higher primary production (Bakun, 1990; Sydeman *et al*., 2014). Similarly, a rise in phytoplankton concentrations due to higher metabolic rates and extended permanence within the euphotic zone in regions of warming has been proposed (Richardson and Schoeman, 2004). Ocean warming can also have other effects on plankton abundance, such as an uneven shift in bloom timing and location of various plankton groups (phenology – match/mismatch) (Richardson, 2008; Henson *et al*., 2013; Barton *et al*., 2016). Higher stratification and more

nutrient-depleted conditions in the surface ocean may lead to changes in ecosystem structure, where smaller phytoplankton will dominate (Bopp *et al*., 2005). Higher ocean CO_2 concentrations (ocean acidification) could lead to higher phytoplankton biomass, depicted as higher Chl *a* concentrations, as a result of excess carbon consumption and/or higher photosynthetic rates (Riebesell *et al*., 2007; Riebesell and Tortell, 2011). Nevertheless, primary producers such as coccolithophores are reported to have a species-specific reaction towards ocean acidification, and general patterns are not easy to identify (Meyer and Riebesell, 2015; Riebesell and Gattuso, 2015). In addition, it has been suggested that the combination of higher CO_2 concentrations coupled with increased light exposure can negatively impact marine primary producers (Gao *et al*., 2012). The regional chapters provide more details on the complex responses of marine organisms to concurrent changes in CO_2 concentrations, ocean temperature, and nutrient availability.

Over the 30-year time-window, increases in diatoms and dinoflagellates were observed in the western and northern North Atlantic (Figure 10.6). McQuatters-Gollop *et al*. (2011) reported increases in phytoplankton in most regions of the North Atlantic after 1980. While this trend seems to be robust, this region exhibits highly variable phytoplankton blooms. These are linked to the North Atlantic Oscillation (NAO), and the magnitude of blooms is related to the mixed-layer depth (Henson *et al*., 2009). It has also been suggested that variations in phytoplankton abundance can be related to expanding or contracting niches as ocean conditions change (Irwin *et al*., 2012; Barton *et al*., 2016). Over shorter time-windows, the changes observed in North Atlantic and Mediterranean phytoplankton abundance are spatially heterogeneous. For example, some parts of the Mediterranean showed a decline in diatom concentrations over the past decade, consistent with reports of a shift from diatom-dominated phytoplankton populations toward non-siliceous types in response to decreasing silica and nitrate concentrations (Goffart *et al*., 2002). A relative lack of phytoplankton data precludes comparable analyses in other ocean basins.

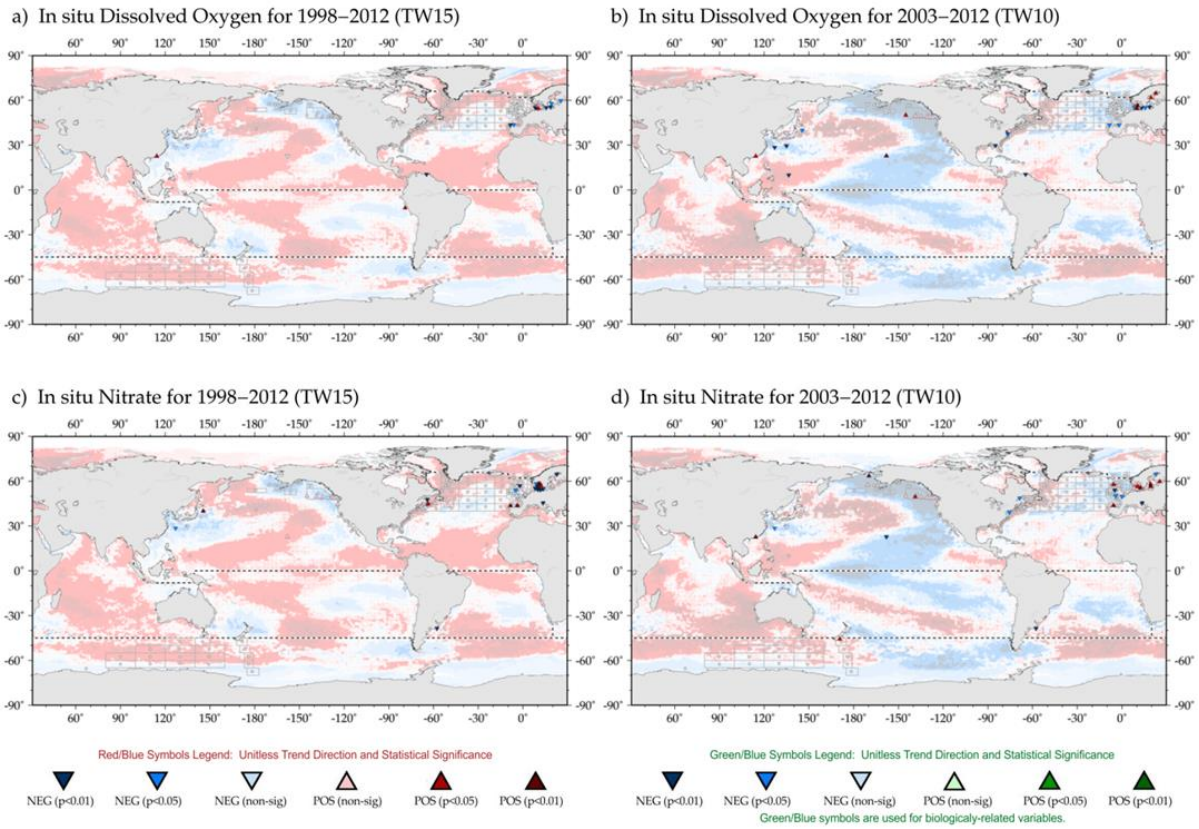


Figure 10.7. Global 15-and-10-year trends (1998–2012 (TW15) and 2003–2012 (TW10), respectively) (a), dissolved oxygen (b); and nitrate concentration (NO_3) (c and d). Background colours indicate rates of change in gridded SST obtained from Reynolds OIv2SST. Variable names according to the IGMETS Explorer (http://igmets.net/explorer/).

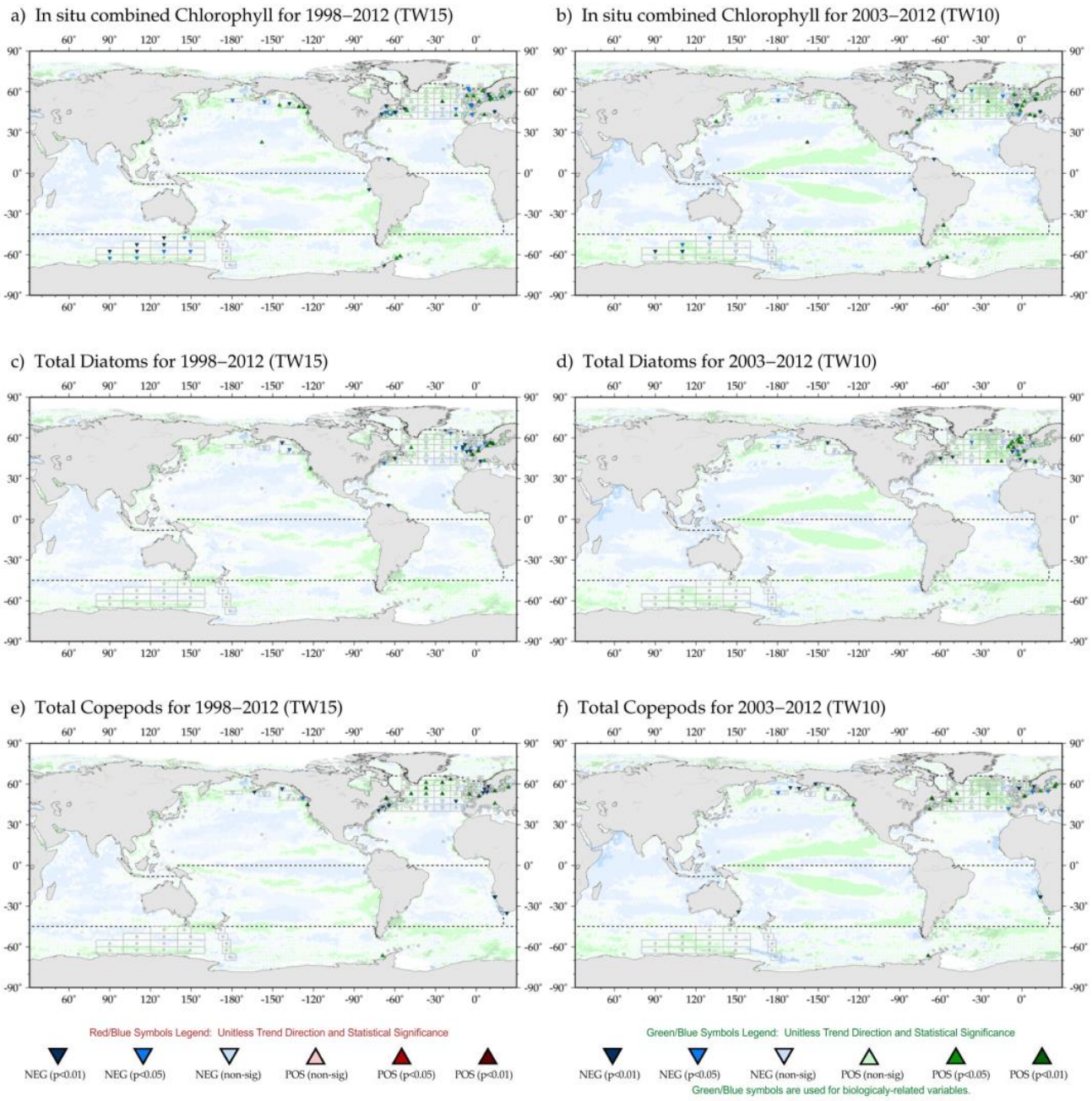


Figure 10.8. Global 15-and-10-year trends (1998–2012 (TW15) and 2003–2012 (TW10), respectively) of *in situ* Chl *a* (a and b); diatom concentration (c and d); and zooplankton (e and f). Background colours indicate rates of change in Chl *a* from SeaWiFS/MODIS-A. Variable names according to the IGMETS Explorer (http://igmets.net/explorer/).

The NAO has been invoked to explain changes in zooplankton populations in the Mediterranean and North Atlantic (Mazzocchi *et al*., 2007; Siokou-Frangou *et al*., 2010; García-Comas *et al*., 2011). Over the past three decades, copepods have largely decreased in the western North Atlantic, but have increased in the eastern North Atlantic and Mediterranean Sea. However, copepod abundance has been highly variable in space and time (Figure 10.8); for example, increases in copepods were observed in the western North Atlantic over the 10-and 5-year windows. Locations of increased Chl *a* were often associated with areas of higher zooplankton biomass, illustrating the foodweb connectivity.

However, most of the changes in zooplankton were non-significant (more information available at http://igmets.net/explorer); this suggests that changes in zooplankton population within the past 15 years may be mostly responding to local drivers (e.g. nutrient inputs and local bloom dynamics), as opposed to large-scale climate drivers (Beaugrand and Reid, 2003; Lejeusne *et al*., 2010). It is important to note that changes within global zooplankton communities (e.g. species composition, seasonal changes), which are key ecosystem characteristics, were not assessed in this global analysis due to limited zooplankton species data, especially outside of the North Atlantic region.

Trends in nutrient concentrations spanning the 5–15-year periods were highly variable across time-series sites (Figures 10.7, 10.9, and 10.10; more information available at http://igmets.net/explorer). At the global level, nitrate is negatively correlated with temperature, which is typical of upwelling systems (Kamykowski and Zentara, 1986, 2005). However, at the local scale, and particularly in coastal regions, other processes may complicate this signal. For example, biologically-driven variability (e.g. taxonomic composition, size structure and abundance of phytoplankton communities) strongly influences nutrient uptake and availability (Richardson, 2008; Mills and Arrigo, 2010; Martiny *et al*., 2013), as do changes in agricultural practices (e.g. fertilizer use and runoff to coastal waters) (Caraco and Cole, 1999; Brodie and Mitchell, 2005). Many of the time series that report increases in nutrient concentrations are located in areas where there has been an increase in Chl *a* (Figure 10.4).

Over time-scales of 10 and 15 years, oxygen data were available for some areas. Surface oxygen concentrations appear to increase in some stations (e.g. North Pacific), while decreasing in others (e.g. off the coast of Spain; Figure 10.7). Looking closely at temperature and oxygen, those locations that exhibited increased oxygen concentrations are located in areas where cooling was observed, as well as high Chl *a* concentrations. Conversely, those stations that showed a decrease in oxygen were in areas that registered warming (Figure 10.7). Thus, these observations are consistent with the predicted temperature-dependent behavior of oxygen (Figure 10.10; Gruber, 2011). Examining even shorter (e.g. 5-year) time-windows, higher variability in oxygen trends was visible (Figure 10.9; i.e. some of the stations that exhibited positive trends change to negative, e.g. the northeastern Pacific), highlighting that local processes exert important controls. However, the pattern stayed consistent with the SST data; areas with increasing temperature were characterized by decreasing oxygen concentrations (Keeling *et al*., 2010; Gruber, 2011). It is important to remember that surface oxygen concentrations depend largely on ocean-atmosphere exchange.

The responses of phytoplankton, zooplankton, and other biogeochemical variables to changes in ocean conditions, as well as the interplay among all of the drivers, vary across regions and are addressed in more detail in each of the regional chapters.

10.4 Conclusions – major findings

Ship-based biogeochemical time series provide the high-quality biological, physical, and chemical measurements that are needed to detect climate change-driven trends in the ocean, assess associated impacts on marine food-webs, and ultimately improve our understanding of changes in marine biodiversity and ecosystems. While the spatial "footprint" of a single time series may be limited (see also Henson *et al*., 2016), coupling observations from multiple time series with synoptic satellite data can improve our understanding of critical processes such as ocean productivity, ecosystem variability, and carbon fluxes on a larger spatial-scale.

By examining the behavior and sensitivity of a variety of physical, chemical, and biological ocean variables over a range of time-scales, some general trends have been highlighted in this chapter. The analyses presented here show a generalized warming trend over the past 30 years. These results are consistent with the IPCC (2013) report as well as other research which have shown significant ocean warming and shifts in the biology over the past several decades. There are, however, regional differences in temperature trends, depending on the time-window considered. These differences are driven by regional and temporal expressions of large-scale climatic forcing and atmospheric teleconnections that can intensify warming and cooling trends in different regions of the ocean. This regional and temporal variability affects biogeochemical cycling (i.e. oxygen, nutrient, carbon), marine foodwebs, and ecosystem services.

The capacity to identify and differentiate anthropogenic and natural climate variations and trends depends largely on the length and location of the time series. Most of the ship-based ecological time series are concentrated in the coastal ocean. Coastal zones are some of the most

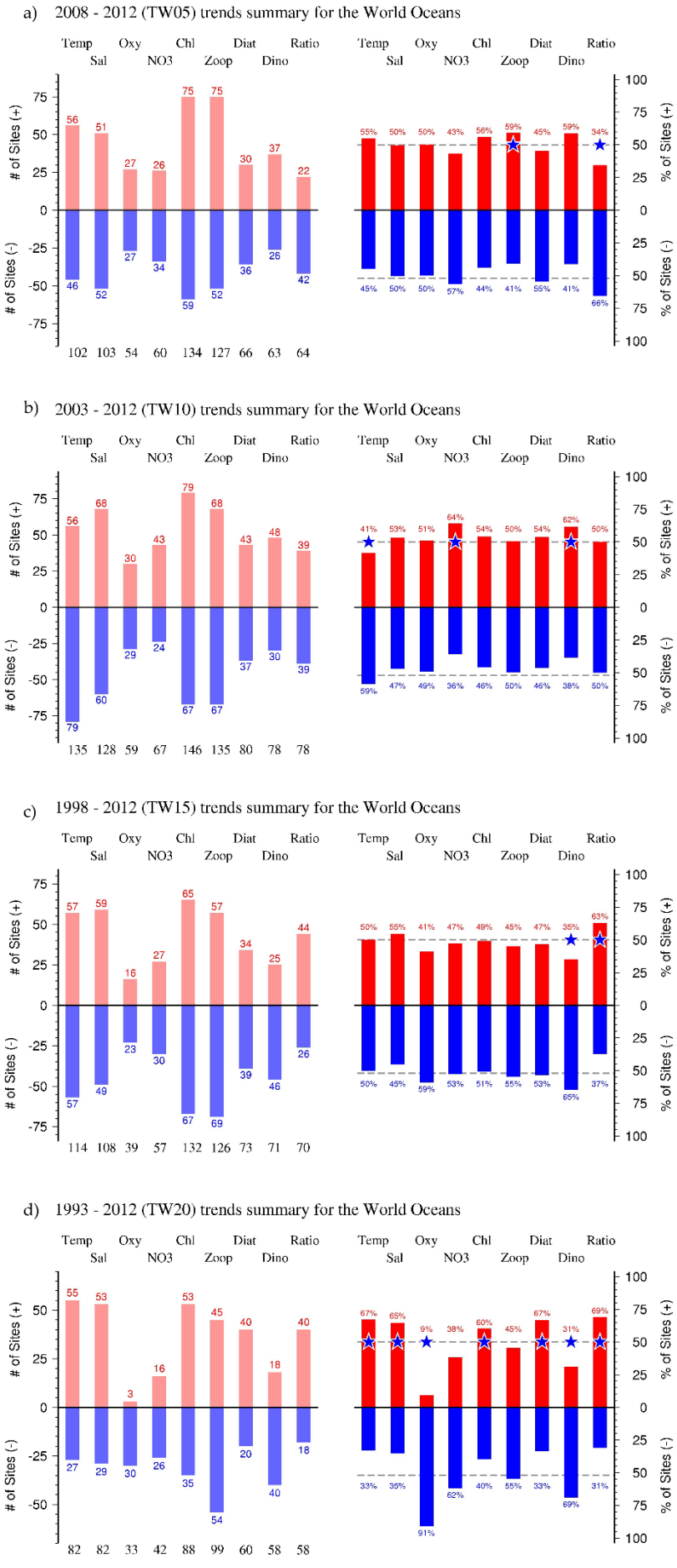


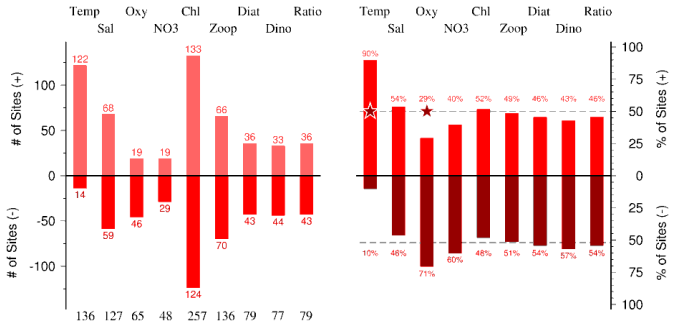
Figure 10.9. BODE (Brief Overviews of Dynamic Ecosystems) plots showing positive and negative trends in selected variables from *in situ* time series in the world's oceans. Time-windows (5, 10, 20, and 30) are indicated in each figure. Significant trends are indicated by the star symbol. Left side illustrates the trend for the absolute number of sites (in no.); panels on the right indicate the percentage of sites showing increasing or decreasing trends. The total number of sites included in this calculation is shown below the figures. Temp: *in situ* temperature; Sal: *in situ* salinity; Oxy: *in situ* oxygen; NO3: *in situ* nitrate; Phyto: *in situ* chlorophyll; Zoop: *in situ* total zooplankton; Diat: *in situ* total diatoms; Dino: *in situ* total dinoflagellates; Ratio: *in situ* ratio of diatoms to dinoflagellates. Data for the 20-year trends for phytoplankton and zooplankton are largely located in the North Atlantic.

productive areas of the ocean and play a critical role in the global carbon cycle (Müller-Karger *et al*., 2005; Chen and Borges, 2009). These areas are important providers of ecosystem goods and services (e.g. food, recreation). Coastal ecosystems are highly dynamic, with strong influences from both ocean and land processes, and are thus more vulnerable to natural and anthropogenic climate forcing. The results shown here highlight differences in biogeochemical trends between coastal and open-ocean regions and among different time-windows. This lends insight into the dominant drivers of coastal and open-ocean ecosystem change and the impacts of decadal (or longer) climate patterns.

While coastal zones in North America and Europe are being monitored, there is a conspicuous lack of biogeochemical time series in other coastal regions around the world, not to mention an almost complete absence of such observational platforms in the open ocean, which limits the capacity of analyses such as presented in this report. A more globally-distributed network of time-series observations over multiple decades will be needed to differentiate between natural and anthropogenic variability. Currently, ocean colour satellite data provide the only synoptic, quasi-biological assessment of the world's oceans, while satellite sea surface temperature, as well as Argo floats, provide information on some of the oceans' physical properties. If biogeochemical time series are essential to documenting and understanding the effects of climate change on ocean resources, how will we maintain and augment the current network of ship-based biogeochemical time series under increased funding pressure? Shrinkage in the already inadequate biogeochemical observing network may result in reductions in sampling and/or long gaps in time-series activities, which will significantly hinder our ability to detect a climate-driven signal. With the development of new technologies, a limited suite of new automated biogeochemical measurements will be possible, but may not be readily accessible to many regions of the world. The majority of biological analysis needed to detect species shift and biodiversity changes will require *in situ* ship-based sampling. This calls for the necessity of securing long-term funding for the maintenance of ship-based time series, together with commitment and support from the global (and not just scientific) community. Without consistent, uninterrupted measurements, it will be impossible to understand the changes and consequences of climate change on the oceans' biogeochemical cycles, biological pump, and marine ecosystems.

A reduction in monitoring capabilities also has important implications for our capacity to predict how the provision of ocean ecosystem services will change in the future and may hamper the establishment of sustainable management strategies. *In situ* measurements are not only critical to monitor ocean health, but also to develop and validate ocean and climate models. As stated previously, *in situ* measurement can serve as a constant biodiversity and ecosystem health "thermometer" used to monitor and predict how goods and services provided by marine ecosystems will be affected in the future (e.g. food resources, flood control, filtering, detoxification; Worm *et al*., 2006; Barange *et al*., 2014). Management of these important marine ecosystem services rely on the high-quality biological and biogeochemical data that time series provide on a regular basis, particularly in coastal areas.

a) 2003–2012 (TW10) correlations between SST and ecological parameters



b) 2003–2012 (TW10) correlations between Chl *a* and ecological parmeters

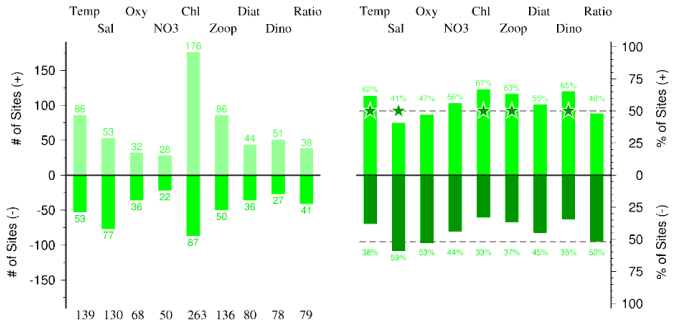


Figure 10.10. Frequency of positive and negative correlations between variables from *in situ* time series and gridded SST (Reynolds OIv2SST) and Chl *a* (satellite derived) computed for a 10-year time-window (2003–2012). Significant trends are indicated by the star symbol. Left side of the figures illustrates the correlation for the absolute number of sites; panels on the right side indicate the percentage of sites showing positive or negative correlation.

10.5 References

Alexander, M. A., Bladé, I., Newman, M., Lanzante, J. R., Lau, N-C., and Scott, J. D. 2002. The atmospheric bridge: the influence of ENSO teleconnections on air–sea interaction over the global oceans. Journal of Climate, 15: 2205–2231, doi:http://dx.doi.org/10.1175/1520-0442(2002)015<2205:TABTIO>2.0.CO;2.

Arrigo, K. R., and van Dijken, G. L. 2011. Secular trends in Arctic Ocean net primary production. Journal of Geophysical Research, 116: C09011, doi:10.1029/2011JC007151.

Bakun, A. 1990. Global climate change and intensification of coastal ocean upwelling. Science, 247(4939): 198–201.

Barange, M., Merino, G., Blanchard, J. L., Scholtens, J., Harle, J., Allison, E. H., Allen, J. I., *et al*. 2014. Impacts of climate change on marine ecosystem production in societies dependent on fisheries. Nature Climate Change, 4(3): 211–216, doi:10.1038/NCLIMATE2119.

Barton, A. D., Irwin, A. J., Finkel, Z. V., and Stock, C. A. 2016. Anthropogenic climate change drives shift and shuffle in North Atlantic phytoplankton communities. Proceedings of the National Academy of Sciences, 113(11): 2964–2969.

Beaugrand, G., and Reid, P. C. 2003. Long-term changes in phytoplankton, zooplankton and salmon linked to climate. Global Change Biology, 9: 801–817, doi:10.1046/j.1365-2486.2003.00632.x.

Beaulieu, C., Henson, S. A., Sarmiento, J. L., Dunne, J. P., Doney, S. C., Rykaczewski, R. R., and Bopp, L. 2013. Factors challenging our ability to detect long-term trends in ocean chlorophyll. Biogeosciences, 10: 2711–2724, doi:10.5194/bg-10-2711-2013.

Behrenfeld, M. J., O'Malley, R. T., Boss, E. S., Westberry, T. K., Graff, J. R., Halsey, K. H., Milligan, A. J., *et al*. 2015. Revaluating ocean warming impacts on global phytoplankton. Nature Climate Change, 6(3): 323–330, doi:10.1038/NCLIMATE2838.

Behrenfeld, M. J., O'Malley, R. T., Siegel, D. A., McClain, C. R., Sarmiento, J. L., Feldman, G. C., Milligan, A. J., *et al*. 2006. Climate-driven trends in contemporary ocean productivity. Nature, 444(7120): 752–755.

Bopp, L., Aumont, O., Cadule, P., Alvain, S., and Gehlen, M. 2005. Response of diatoms distribution to global warming and potential implications: A global model study. Geophysical Research Letters, 32(19): L19606, doi:10.1029/2005GL023653.

Boyce, D. G. Lewis, M. R., and Worm, B. 2010. Global phytoplankton decline over the past century. Nature, 466(7306): 591–596, doi:10.1038/nature09268.

Brodie, J. E., and Mitchell, A. W. 2005. Nutrients in Australian tropical rivers: changes with agricultural development and implications for receiving environments. Marine and Freshwater Research, 56: 279–302.

Caraco, N. F., and Cole, J. J. 1999. Human impact on nitrate export: an analysis using major world rivers. Ambio, 28: 167–170.

Chavez, F. P., Messié, M., and Pennington, J. T. 2011. Marine primary production in relation to climate variability and change. Annual Review of Marine Science, 3: 227–260.

Chavez, F. P., Ryan, J., Lluch-Cota, S. E., and Ñiquen, M. 2003. From anchovies to sardines and back: multidecadal change in the Pacific Ocean. Science, 299(5604): 217–221.

Chen, C. T. A., and Borges, A. V. 2009. Reconciling opposing views on carbon cycling in the coastal ocean: continental shelves as sinks and near-shore ecosystems as sources of atmospheric CO_2. Deep-Sea Research II: Topical Studies in Oceanography, 56(8): 578–590, doi:10.1016/j.dsr2.2009.01.001.

Church, M. J., Lomas, M. W., and Müller-Karger, F. 2013. Sea change: Charting the course for biogeochemical ocean time-series research in a new millennium. Deep-Sea Research II: Topical Studies in Oceanography, 93: 2–15.

Dave, A. C., and Lozier, M. S. 2013. Examining the global record of interannual variability in stratification and marine productivity in the low-latitude and mid-latitude ocean. Journal of Geophysical Research: Oceans, 118: 3114–3127, doi:10.1002/jgrc.20224.

Deser, C., Phillips, A. S., and Alexander, M. A. 2010. Twentieth century tropical sea surface temperature trends revisited. Geophysical Research Letters, 37(10): L1070, doi: 10.1029/2010GL043321.

Doney, S. C. 2006. Oceanography—Plankton in a warmer world, Nature, 444(7120): 695–696, doi:10.1038/444695a.

Doney, S. C., Bopp, L., and Long, M. C. 2014. Historical and future trends in ocean climate and biogeochemistry. Oceanography, 27(1): 108–119, http://dx.doi.org/10.5670/oceanog.2014.14.

Dong, L., and Zhou, T. 2014. The formation of the recent cooling in the eastern tropical Pacific Ocean and the associated climate impacts: A competition of global warming, IPO, and AMO. Journal of Geophysical Research: Atmospheres, 119(19): 11272–11287, doi:10.1002/2013JD021395.

Ducklow, H. W., Fraser, W. R., Meredith, M. P., Stammerjohn, S. E., Doney, S. C., Martinson, D. G., Sailley, S. F., *et al*. 2013. West Antarctic Peninsula: An ice-dependent coastal marine ecosystem in transition. Oceanography, 26(3): 190–203, http://dx.doi.org/10.5670/oceanog.2013.62.

Enfield, D. B., and Mestas-Nuñez, A. M. 2000. Global modes of ENSO and non-ENSO sea surface temperature variability and their associations with climate. *In* El Niño and the Southern Oscillation: Multiscale Variability and Global and Regional Impacts, pp. 89–112). Ed. by H. F. Diaz, and V. Markgraf. Cambridge University Press. 512 pp.

Enfield, D. B., Mestas-Nuñez, A. M., and Trimble, P. J. 2001. The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental US. Geophysical Research Letters, 28(10): 2077–2080.

Gao, K., Xu, J., Gao, G., Li, Y., Hutchins, D. A., Huang, B., Wang, L., *et al*. 2012. Rising CO_2 and increased light exposure synergistically reduce marine primary productivity. Nature Climate Change, *2*(7): 519–523.

García-Comasa, C., Stemmanna, L., Ibaneza, F., Berlinea, L., Mazzocchi, M., Gasparinia, G. S., Picherala, M., *et al*. 2011. Zooplankton long-term changes in the NW Mediterranean Sea: Decadal periodicity forced by winter hydrographic conditions related to large-scale atmospheric changes? Journal of Marine Systems, 87(3–4): 216–226.

Goffart, A., Hecq, J. H., and Legendre, L. 2002. Changes in the development of the winter-spring phytoplankton bloom in the Bay of Calvi (NW Mediterranean) over the last two decades: a response to changing climate? Marine Ecology Progress Series, 236: 45–60, doi:10.3354/meps236045.

Gregg, W. W., and Rousseaux, C. S. 2014. Decadal trends in global pelagic ocean chlorophyll: A new assessment integrating multiple satellites, *in situ* data, and models. Journal of Geophysical Research: Oceans, 119(9): 5921–5933.

Gruber, N. 2011. Warming up, turning sour, losing breath: ocean biogeochemistry under global change. Philosophical Transactions of the Royal Society A, 369: 1980–1996, doi:10.1098/rsta.2011.0003.

Han, W., Vialard, J., McPhaden, M. J., Lee, T., Masumoto, Y., Feng, M., and De Ruijter, W. P. 2014. Indian Ocean decadal variability: A review. Bulletin of the American Meteorological Society, 95(11): 1679–1703.

Henson, S. A. 2014. Slow science: the value of long ocean biogeochemistry records. Philosophical Transactions of the Royal Society A, 372(2025): doi:10.1098/rsta.2013.0334.

Henson, S. A., Beaulieu, C., and Lampitt, R. 2016. Observing climate change trends in ocean biogeochemistry: when and where. Global Change Biology, *22*(4): 1561–1571.

Henson, S., Cole, H., Beaulieu, C., and Yool, A. 2013. The impact of global warming on seasonality of ocean primary production. Biogeosciences, 10(6): 4357–4369, doi:10.5194/bg-10-4357-2013.

Henson, S. A., Dunne, J., and Sarmiento, J. L. 2009. Decadal variability in North Atlantic phytoplankton blooms. Journal of Geophysical Research, 114: C04013, doi:10.1029/2008JC005139.

Henson, S. E., Sarmiento, J., Dunne, J., Bopp, L., Lima, I., Doney, S., John, J., *et al*. 2010. Detection of anthropogenic climate change in the satellite records of ocean chlorophyll and productivity. Biogeosciences, 7: 621–640.

Hoegh-Guldberg, O., and Bruno, J. F. 2010. The impact of climate change on the world's marine ecosystems. Science, 328: 1523–1528.

Hoegh-Guldberg, O., Cai, R., Poloczanska, E. S., Brewer, P. G., Sundby, S., Hilmi, H., Fabry, V. J., *et al*. 2014. The Ocean. *In* Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects, pp. 1655–1731. Ed. by V. R. Barros, C. B. Field, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, M. Chatterjee, *et al.* Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge and New York. 688 pp.

Hurrell, J. W., and Deser, C. 2010. North Atlantic climate variability: The role of the North Atlantic Oscillation. Journal of Marine Systems, 79 (3–4): 231–244.

IPCC. 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Ed. by T. F. Stocker, D. Qin, G-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, *et al*. Cambridge University Press, Cambridge and New York. 1535 pp.

Irwin, A. J., Nelles, A., M., and Finkel, Z. V. 2012. Phytoplankton niches estimated from field data. Limnology and Oceanography, 57(3): 787–797, doi:10.4319/lo.2012.57.3.0787.

Kamykowski, D., and Zentara, J. 1986. Predicting plant nutrient concentrations from temperature and sigma-t in the world ocean. Deep-Sea Research, 33: 89–105.

Kamykowski, D., and Zentara, J. 2005. Changes in world ocean nitrate availability through the 20th century. Deep-Sea Research I, 52: 1719–1744.

Karl, D. M. 2010. Oceanic ecosystem time-series programs. Oceanography, 23(3): 104–125.

Karl, T. R., Arguez, A., Huang, B., Lawrimore, J. H., McMahon, J. R., Menne, M. J., Peterson, T. C., *et al*. 2015. Possible artifacts of data biases in the recent global surface warming hiatus. Science, 348(6242): 1469–1472, doi: 10.1126/science.aaa5632.

Keeling, R. F., Körtzinger, A., and Gruber, N. 2010. Ocean deoxygenation in a warming world. Annual Review of Marine Science, 2: 199–229.

Kempt, A. E., and Villareal, T. A. 2013. High diatom production and export in stratified waters – A potential negative feedback to global warming. Progress in Oceanography, 119: 4–23.

Knudsen, M. F., Seidenkrantz, M. S., Jacobsen, B. H., and Kuijpers, A. 2011. Tracking the Atlantic Multidecadal Oscillation through the last 8,000 years. Nature Communications, 2: 178.

Kosaka, Y., and Xie, S. P. 2013. Recent global-warming hiatus tied to equatorial Pacific surface cooling. Nature, 501(7467): 403–407.

Kwok, R., and Comiso, J. C. 2002. Spatial patterns of variability in Antarctic surface temperature: Connections to the Southern Hemisphere Annular Mode and the Southern Oscillation. Geophysical Research Letters, 29(14): 50-1–50-4, doi:10.1029/2002GL015415.

Laws, E. A., Falkowski, P. G., Smith, W. O., Ducklow, H., and McCarthy, J. J. 2000. Temperature effects on export production in the open ocean. Global Biogeochemical Cycles, 14(4): 1231–1246.

Lejeusne, C., Chevaldonné, P., Pergent-Martini, C., Boudouresque, C. F., and Pérez, T. 2010. Climate change effects on a miniature ocean: the highly diverse, highly impacted Mediterranean Sea. Trends in Ecology & Evolution, 25(4): 250–260, doi:http://dx.doi.org/10.1016/j.tree.2009.10.009.

Marshall, J., Armour, K. C., Scott, J. R., Kostov, Y., Hausmann, U., Ferreira, D., Shepherd, T. G., *et al*. 2014. The ocean's role in polar climate change: asymmetric Arctic and Antarctic responses to greenhouse gas and ozone forcing. Philosophical Transactions of the Royal Society A, 372: 20130040, doi:10.1098/rsta.2013.0040.

Martiny, A. C., Pham, C. T. A., Primeau, F. W., Vrugt, J. A., Moore, J. K., Levin, S. A., and Lomas, M. W. 2013. Strong latitudinal patterns in the elemental ratios of marine plankton and organic matter. Nature Geoscience, 6(4): 279–283, doi:http://dx.doi.org/10.1038/ngeo1757.

Mazzocchi, M. G., Christoub, E. D., Di Capuaa, I., Fernández de Puellesc, M., Fonda-Umanid, S., Molineroe, J. C., Nivalf, P., *et al*. 2007. Temporal variability of *Centropages typicus* in the Mediterranean Sea over seasonal-to-decadal scales. Progress in Oceanography, 72(2–3): 214–232, doi:http://dx.doi.org/10.1016/j.pocean.2007.01.004.

Meredith, M. P., and King, J. C. 2005. Rapid climate change in the ocean west of the Antarctic Peninsula during the second half of the 20th century. Geophysical Research Letters, 32: L19604, doi:10.1029/2005GL024042.

Meyer, J., and Riebesell, U. 2015. Reviews and syntheses: Responses of coccolithophores to ocean acidification: a meta-analysis. Biogeosciences, 12(6): 1671–1682, doi:10.5194/bg-12-1671-2015.

Mills, M. M., and Arrigo, K. R. 2010. Magnitude of oceanic nitrogen fixation influenced by the nutrient uptake ratio of phytoplankton. Nature Geoscience, *3*(6): 412–416.

Morel, A., Gentili, B., Claustre, H., Babin, M., Bricaud, A., Ras, J., and Tieche, F. 2007. Optical properties of the "clearest" natural waters. Limnology and Oceanography, 52(1): 217–229.

McQuatters-Gollop, A., Reid, P. C., Edwards, M., Burkill, P. H., Castellani, C., Batten, S., Gieskes, W., *et al*. 2011. Is there a decline in marine phytoplankton? Nature, 472(7342): E6–E7.

Müller-Karger, F. E., Varela, R., Thunell, R., Luerssen, R., Hu, C., and Walsh, J. J. 2005. The importance of continental margins in the global carbon cycle. Geophysical Research Letters, 32: L01602, doi:10.1029/2004GL021346.

Nobre, P., and Shukla, J. 1996. Variations of sea surface temperature, wind stress, and rainfall over the tropical Atlantic and South America. Journal of Climate, 9: 2464–2479, doi:http://dx.doi.org/10.1175/1520-0442(1996)009<2464:VOSSTW>2.0.CO;2.

Overland, J. E., Alheit, J., Bakun, A., Hurrell, J. W., Mackas, D. L., and Miller, A. J. 2010. Climate controls on marine ecosystems and fish populations. Journal of Marine Systems, 79(3): 305–315.

Overland, J. E., Percival, D. B., and Mofjeld, H. O. 2006. Regime shifts and red noise in the North Pacific. Deep-Sea Research I: Oceanographic Research Papers, 53(4): 582–588.

Polovina, J. J., Howell, E. A., and Abecassis, M. 2008. Ocean's least productive waters are expanding. Geophysical Research Letters, 35: L03618, doi:10.1029/2007GL031745.

Rahmstorf, S., Feulner, G., Mann, M. E., Robinson, A., Rutherford, S., and Schaffernicht, E. J. 2015. Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation. Nature Climate Change, 5(5): 475–480, doi:10.1038/NCLIMATE2554.

Randel, W. J., and Wu, F. 1999. Cooling of the Arctic and Antarctic polar stratosphere due to ozone depletion. Journal of Climate, 12: 1467–1479, doi:10.1175/1520-0442(1999)012<1467:COTAAA>2.0.CO;2.

Richardson, A. J., and Schoeman, D. S. 2004. Climate impact on plankton ecosystems in the Northeast Atlantic. Science, 305(5690): 1609–1612, doi:10.1126/science.1100958.

Richardson, A. 2008. In hot water: zooplankton and climate change. ICES Journal of Marine Science, 65(3): 279–295, doi:10.1093/icesjms/fsn028.

Riebesell, U., and Gattuso, J-P. 2015. Lessons learned from ocean acidification research. Nature Climate Change, 5(1): 12–14.

Riebesell, U., Schulz, K. G., Bellerby, R. G. J., Botros, M., Fritsche, P., Meyerhöfer, M., Neill, C., *et al*. 2007. Enhanced biological carbon consumption in a high CO^2 ocean. Nature, 450(7169): 545–548.

Riebesell, U., and Tortell, P. D. 2011. Effects of ocean acidification on pelagic organisms and ecosystems. *In* Ocean Acidification, pp. 99–121. Ed. by J-P. Gattuso, and L. Hansson. Oxford University Press. 326 pp.

Serreze, M. C., and Barry, R. G. 2011. Processes and impacts of Arctic amplification: A research synthesis. Global and Planetary Change, 77(1–2): 85–96, doi:http://dx.doi.org/10.1016/j.gloplacha.2011.03.004.

Siegel, D. A., Maritorena, S., Nelson, N. B., Behrenfeld, M. J., and McClain, C. R. 2005. Colored dissolved organic matter and its influence on the satellite-based characterization of the ocean biosphere. Geophysical Research Letters, 32: L20605, doi:10.1029/2005GL024310.

Siegel, D. A., Behrenfeld, M. J., Maritorena, S., McClain, C. R., Antoine, D., Bailey, S. W., Bontempi, P. S., *et al*. 2013. Regional to global assessments of phytoplankton dynamics from the SeaWiFS mission. Remote Sensing of Environment, 135: 77–91.

Signorini, S. R., Franz, B. A., and McClain, C. R. 2015. Chlorophyll variability in the oligotrophic gyres: mechanisms, seasonality and trends. Frontiers in Marine Science, 2: 1, doi:10.3389/fmars.2015.00001.

Siokou-Frangou, I., Christaki, U., Mazzocchi, M. G., Montresor, M., Ribera d'Alcalá, M., Vaqué, D., and Zingone, A. 2010. Plankton in the open Mediterranean Sea: a review. Biogeosciences, 7, 1543-1586.

Steig, E. J., Schneider, D. P., Rutherford, S. D., Mann, M. E., Comiso, J. E., and Shindell, D. T. 2009. Warming of the Antarctic ice-sheet surface since the 1957 International Geophysical Year. Nature, 457: 459–462.

Sydeman, W. J., García-Reyes, M., Schoeman, D. S., Rykaczewski, R. R., Thompson, S. A., Black, B. A., and Bograd, S. J. 2014. Climate change and wind intensification in coastal upwelling ecosystems. Science, 345(6192): 77–80.

Thompson, D. W. J., and Solomon, S. 2002. Interpretation of recent southern hemisphere climate change. Science, 296(5569): 895–899, doi:10.1126/science.1069270.

Vantrepotte, V., and Mélin, F. 2009. Temporal variability of 10-year global SeaWiFS time series of phytoplankton chlorophyll a concentration. ICES Journal of Marine Science, 66(7): 1547–1556, doi:10.1093/icesjms/fsp107.

Vantrepotte, V., and Mélin, F. 2011. Inter-annual variations in the SeaWiFS global chlorophyll a concentration (1997–2007). Deep-Sea Research I: Oceanographic Research Papers, 58(4): 429–441.

Venegas, S. A., Mysak, L. A., and Straub, D. N. 1997. Atmosphere–ocean coupled variability in the South Atlantic. Journal of Climate, 10: 2904–2920, doi:http://dx.doi.org/10.1175/1520-0442(1997)010<2904:AOCVIT>2.0.CO;2.

Visbeck, M. H., Hurrell, J. W., Polvani, L., and Cullen, H. M. 2001. The North Atlantic Oscillation: Past, present, and future. Proceedings of the National Academy of Sciences of the United States of America, 98(23): 12876–12877, doi:10.1073/pnas.231391598.

Worm, B., Barbier, E. B., Beaumont, N., Duffy, J. E., Folke, C., Halpern, B. S., Jackson, J. B. C., *et al*. 2006. Impacts of biodiversity loss on ocean ecosystem services. Science, 314(5800): 787–790, doi:10.1126/science.1132294.

Yu, L., Zhang, Z., Zhou, M., Zhong, S., Lenschow, D., Hsu, H., Wu, H., *et al*. 2012. Influence of the Antarctic Oscillation, the Pacific–South American modes and the El Niño–Southern Oscillation on the Antarctic surface temperature and pressure variations. Antarctic Science, 24(01): 59–76.

Yuras, G., Ulloa, O., and Hormazábal, S. 2005. On the annual cycle of coastal and open ocean satellite chlorophyll off Chile (18°–40°S). Geophysical Research Letters, 32(23), doi:http://dx.doi.org/10.1029/2005GL023946.

Zhang, J., Spitz, Y. H., Steele, M., Ashjian, C., Campbell, R., Berline, L., and Matrai, P. 2010. Modeling the impact of declining sea ice on the Arctic marine planktonic ecosystem. Journal of Gephysical Research, 115: C10015, doi:10.1029/2009JC005387.